

First of all, we would like to thank you for all your comments (shown in black), which greatly helped us improve our manuscript. Below, we provide our detailed point-by-point responses (in blue). We have resubmitted the revised manuscript accordingly.

In addition, we would like to inform you that the manuscript title has been changed from “*Linear trends of temperature, salinity, and oxygen in the North Pacific based on GOBAI-O₂ over 2 decades and their controlling factors*” to “*Revealing Hidden Oxygen Variability in the North Pacific: A Two-Decade Analysis Using GOBAI-O₂.*”

Responses to the comment from Reviewer #1

The authors have made a genuine effort to address the reviewer concerns and the manuscript is notably improved; however, several key issues remain unresolved, including the absence of a statistical assessment of trend robustness relative to uncertainty, an incomplete treatment of known optode biases, mechanistic interpretations that extend beyond what the data can firmly support, an only partly developed articulation of what is genuinely novel in this work, and persistent language and clarity problems. Overall, I recommend major revision (though this could be reduced to minor if these issues are satisfactorily addressed). The study has strong potential, but it will require more rigorous handling of uncertainty and a more cautious, evidence-based interpretation before it can serve as a reliable contribution to our understanding of North Pacific oxygen variability.

General Assessment

The manuscript is significantly improved. The authors have:

- added extensive comparisons with Ito et al. (2017) and briefly with Ito 2024 and Kolodziejczyk 2024.
- incorporated uncertainty fields, described their origin (Sharp et al., 2023), and added figures showing uncertainty alongside trends.
- added methodological justification for the 1-m vertical interpolation, including sensitivity tests (Figures S1–S2).
- clarified the decomposition of oxygen change and added a schematic.
- expanded discussion of physical mechanisms (northward front migration, OML retreat).
- improved figure presentation in several places.

These are meaningful improvements. However, several issues persist that limit the manuscript’s robustness, especially regarding uncertainty interpretation, sensor bias, and the strength of physical attribution.

Major remaining issues

1. The manuscript now includes uncertainty fields and explains the GOBAI-O₂ uncertainty

components. However the interpretation of uncertainty relative to trends is still weak. On several figures (e.g., Fig. 1O–U), the magnitude of oxygen trends is comparable to the mean uncertainty, yet the discussion continues to present the spatial patterns as physically meaningful without a formal test of significance. No statistical test (e.g., trend significance vs. local uncertainty, confidence intervals, fdr correction, etc.) is performed. The authors state that “the observed trends are spatially coherent and smoothly connected,” but spatial coherence cannot substitute for uncertainty quantification. The authors need to explicitly state where trends are robust vs. indistinguishable from uncertainty. Even a simple criterion (e.g., $|\text{trend}| > \text{mean uncertainty}$) or a bootstrap approach would be acceptable.

In response to this comment, we added their statistical significance using a Student’s *t*-test with effective degrees of freedom that account for lag-1 autocorrelation (Figs. 1a–u and 3) for the estimated linear trends. The oxygen trends (Fig. 1(o–u)) are shown to be largely statistically significant, particularly below the surface (Fig. 1o). In the revised manuscript, readers can now clearly identify which trends are statistically significant. The new results indicate that nearly all linear trends, particularly those below the surface, are statistically significant.

> Even a simple criterion (e.g., $|\text{trend}| > \text{mean uncertainty}$)

Thank you for this suggestion. The trend and the mean uncertainty have different units, and so we did not use this criterion.

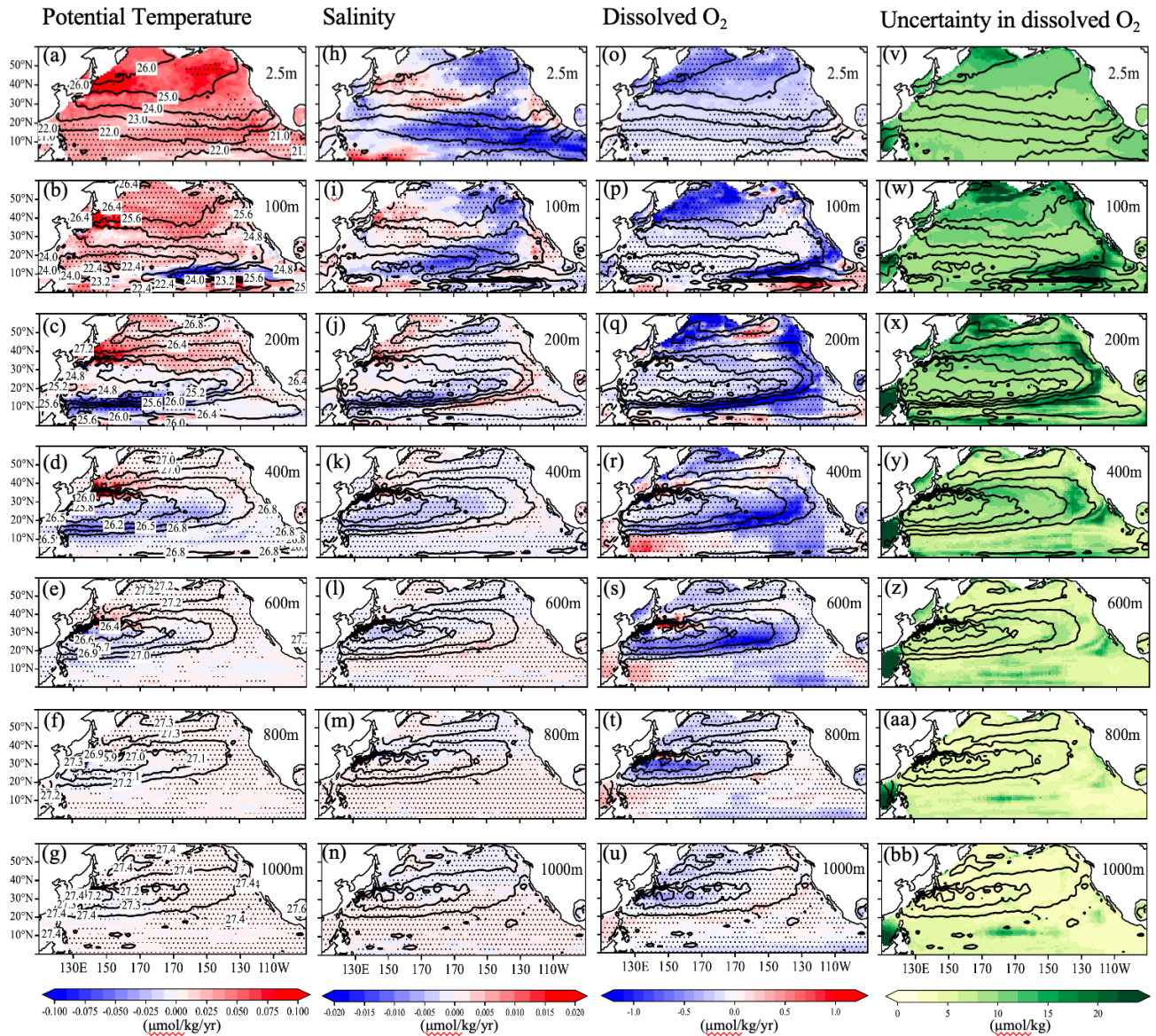
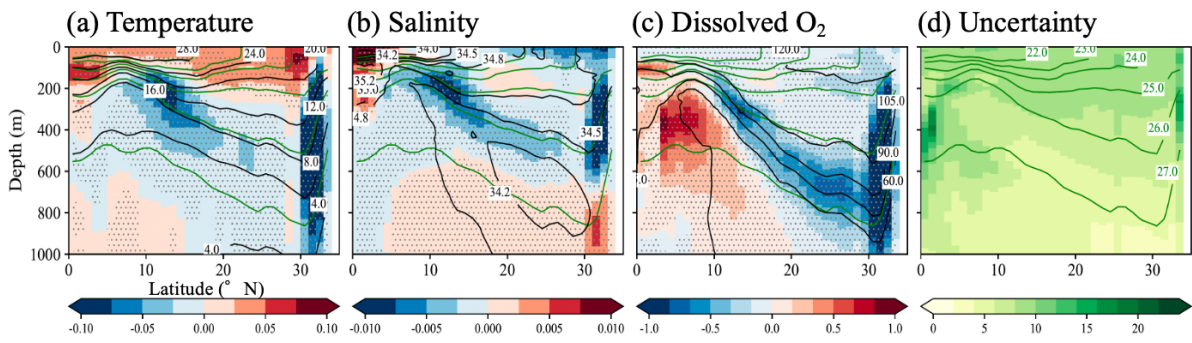


Figure 1 in revised manuscript: Horizontal distributions of linear trends ($\mu\text{mol/kg/yr}$) in (a–g) potential temperature, (h–n) salinity, and (o–u) dissolved oxygen (O_2) during the observational period at depths of 0, 100, 200, 400, 600, 800, and 1000 m, respectively. Hatched areas indicate statistically significant trends at the 95% confidence level based on a Student’s t-test with effective degrees of freedom accounting for temporal autocorrelation. Trend significance was evaluated using a t-test with effective degrees of freedom accounting for lag-1 autocorrelation. Contours denote potential density at each depth. Labels for the potential density are shown only in the potential temperature sections. Corresponding distributions of the mean uncertainty in dissolved O_2 ($\mu\text{mol/kg}$) are presented in panels (v–bb).

137° E line



165° E line

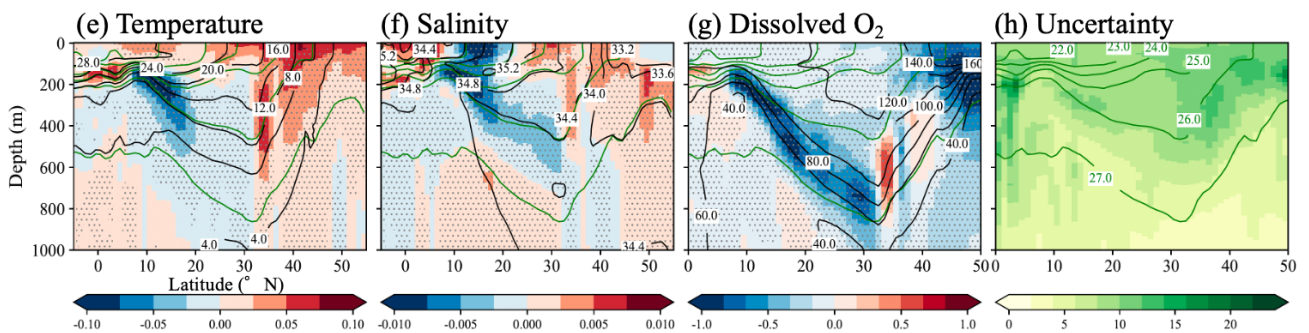


Figure 3 in the revised manuscript: Vertical sections showing linear trends in potential temperature (a, e), salinity (b, f), and dissolved O₂ (c, g) along the 137°E and 165°E meridians, respectively. Corresponding vertical sections of the mean uncertainty are presented in panels (d) and (h). Black contour lines indicate the mean potential temperature (a, e), salinity (b, f), and dissolved oxygen (c, g) over the period 2004–2023, while green contour lines represent the mean potential density. Labels for the potential density are shown only in the uncertainty sections. Hatched areas indicate statistically significant trends at the 95% confidence level based on a Student’s t-test with effective degrees of freedom accounting for temporal autocorrelation. Trend significance was evaluated using a t-test with effective degrees of freedom accounting for lag-1 autocorrelation.

2. In the response, the authors acknowledge known negative biases ($\sim -2.7 \mu\text{mol kg}^{-1}$) from air-calibrated floats, but in the manuscript, this appears in one paragraph with no assessment of its impact on long-term trends, regional patterns (e.g., oxycline-intensifying bias) or comparisons with shipboard observations. Given that GOBAI-O2 is trained directly on such floats, the bias issue cannot simply be acknowledged, it must be integrated into the uncertainty interpretation. Consider adding a subsection explaining how a systematic offset would (or would not) affect the trend estimates, particularly in regions where variability is small. If not quantified, the authors should explicitly state the limitation.

It is difficult to directly assess where the negative biases of the air-calibration float lie within each region for the current dataset. Instead of quantifying, we have noted this issue for readers by including a cautionary note in Section 4.

The revised section now reads:

“Recent work by Bushinsky et al. [2025] has reported the presence of a systematic negative bias (approximately $-2.7 \mu\text{mol kg}^{-1}$) in air-calibrated BGC-Argo oxygen measurements compared with ship-based reference profiles. This bias does not appear to be explicitly corrected in the GOBAI-O₂, and therefore may affect the magnitude of the estimated oxygen trends—potentially enhancing negative trends or suppressing positive ones in regions with dense float sampling. Such biases may also influence the apparent vertical structure of oxycline. In the North Pacific, regions with high float density—such as the Kuroshio–Oyashio transition zone, the North American coastal region, and the vicinity of Hawaii—may be particularly affected (see Fig. 1 of Sharp et al., 2023). While a constant offset would not directly alter linear trend estimates, any time-varying bias associated with sensor behavior or sampling depth could introduce spurious trends. A quantitative evaluation is not feasible at present due to the lack of temporally continuous ship-based reference data at the spatial scales. This limitation should therefore be kept in mind when interpreting the O₂ trends reported here.”

3. The revised manuscript still pushes some mechanistic explanations too far relative to the observational evidence provided.

Examples:

-The link between the tropical OML retreat and NECC weakening/poleward shift (Section 3.3.2) is plausible but not demonstrated. The use of OFES output is too qualitative to support the claims.

-The northward migration of the subtropical–subarctic front is invoked repeatedly, but no independent metric (e.g., SSH fronts, SSS gradients, isopycnal outcrop latitude) is quantitatively analyzed in the manuscript.

The authors should soften language (“suggests”, “is consistent with”, “is likely influenced by”) unless independent evidence is shown in the figures.

>-The link between the tropical OML retreat and NECC weakening/poleward shift (Section 3.3.2) is plausible but not demonstrated. The use of OFES output is too qualitative to support the claims.

According to this comment, we have revised the text in Section 3.3.2 to soften the language, replacing causal statements with more cautious expressions such as “is consistent with”, “suggests”, and “may influence”.

The part can be read now in Section 3.3.2:

“The westward penetration of the OML is slow and occurs between two eastward-extending tongues

of high O₂ water originating near the equator [Reid, 1997] (Fig. S6). The observed O₂ increase on the 26.8–27.2 σ_θ surfaces (Fig. 3c, g and Fig. 4c, g) is consistent with a weakening and north-poleward shift of the interdecadal NECC mode. The subsurface O₂ increase, particularly below 400m depth (Fig. 1r–u), is therefore likely influenced by these circulation changes, potentially allowing higher-O₂ water to extend westward (Fig. S6). In addition, shoaling of isopycnal surfaces near the equator indicates a northward shift of the boundary between the tropical and subtropical gyres along 137°E line during the observational period.”

In addition, we have included the horizontal distributions of the mean dissolved O₂ at several depths in the Supplementary Material (Figure S6) to aid readers who may be less familiar with the spatial patterns of dissolved O₂ in the North Pacific. We expect that this figure will help understand our explanations.

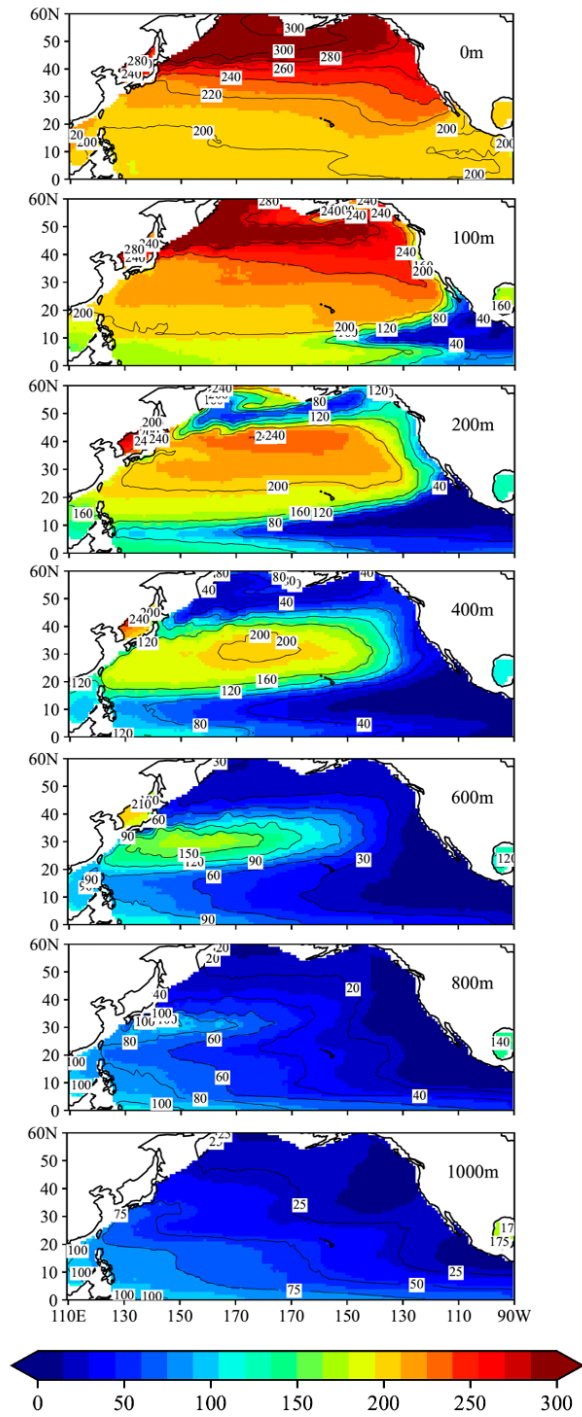


Figure S6 in the revised manuscript. Horizontal distribution of averaged dissolved O_2 ($\mu\text{mol/lg}$) at depths of 0, 100, 200, 400, 600, 800, and 1000 m, respectively, during 2004–2023.

>-The northward migration of the subtropical–subarctic front is invoked repeatedly, but no independent metric (e.g., SSH fronts, SSS gradients, isopycnal outcrop latitude) is quantitatively analyzed in the manuscript.

In response to this comment, we note that Figure 6 already provides an independent metric relevant to the northward migration of the subtropical–subarctic front, namely the latitude of isopycnal outcrops. The outcrop latitudes are evaluated for March, which corresponds to the season of the deepest mixed layer depth in the North Pacific (Ohno et al., 2009) and is therefore commonly used in outcropping and ventilation studies in this region (e.g., Mecking and Drushka, 2024). As shown in Figure 6, the northward displacement of the 25.0 σ_θ isopycnal outcrop directly reflects the migration of the subtropical–subarctic frontal zone. We therefore consider that the manuscript already includes a quantitative and physically grounded indicator of the frontal migration discussed in the text.

Relating references:

Ohno, Y., Iwasaka, N., Kobashi, F., & Sato, Y. (2009). Mixed layer depth climatology of the North Pacific based on Argo observations. *Journal of Oceanography*, 65(1), 1–16.

<https://doi.org/10.1007/s10872-009-0001-4>

Mecking, S., & Drushka, K. (2024). Linking northeastern North Pacific oxygen changes to upstream surface outcrop variations. *Biogeosciences*, 21(5), 1117–1133. <https://doi.org/10.5194/bg-21-1117-2024>

4. The comparison with Ito et al. (2017) is improved, but the manuscript still reads at times as confirmation of known patterns rather than revealing new insights emerging uniquely from GOBAI-O₂.

Consider adding a short paragraph in the Discussion explicitly stating:

- What patterns are new,
- Why these patterns are only recoverable with BGC-Argo and GOBAI-O₂,
- How this contributes to advancing our understanding beyond previous basin-scale syntheses.

We thank the reviewer for this constructive suggestion. In response, we have added a new paragraph to the Discussion and Conclusion section (Section 4) explicitly clarifying (i) which spatial and isopycnal-scale O₂ trends are newly identified in this study, (ii) why these patterns are only recoverable using BGC-Argo observations and the GOBAI-O₂ product, and (iii) how our results extend previous basin-scale syntheses beyond confirmation of known features. The added paragraph is as follows.

“Although many of the large-scale features identified here resemble those reported by Ito et al. (2017), our analysis reveals regional and isopycnal-scale structures that were previously unresolved. In particular, the positive oxygen trends in the Kuroshio–Oyashio Transition Zone, the northeastern North Pacific along the 26.8–27.0 σ_θ density surfaces, and the enhanced subsurface O₂ increase in the tropical western Pacific below 400 m were not clearly distinguished in earlier climatology-based studies. These improvements arise because GOBAI-O₂ integrates high-frequency BGC-Argo oxygen observations with a spatially consistent mapping scheme, reducing observational gaps and sampling biases in

dynamically active regions. This demonstrates that regional reoxygenation signals can coexist with large-scale deoxygenation, and highlights the importance of sustained BGC-Argo observations for detecting emerging changes in ocean biogeochemistry.”

The following part was also added in the revised manuscript of Section 3.2.

“Whereas data gaps increase with depth in Ito et al. (2017), the GOBAI-O₂ product provides more spatially continuous coverage, yielding distributions that remain consistent with surrounding regions.”

5. The new schematic (S5) helps, but the main text remains mathematically dense and could be streamlined. Additionally, several terms include both $\partial z/\partial t$ and $\partial X/\partial z$ interactions that need clearer physical interpretation.

Consider keeping the decomposition but include a brief physical interpretation table in the main text (e.g., “Term (ii): vertical heave; Term (iii): solubility change”, etc.).

We thank the reviewer for this helpful suggestion. We agree that clarifying the physical interpretation of the decomposition is important for readability. In the revised manuscript, we already provide a concise physical interpretation of the major terms directly in the main text, immediately following Eqs. (2) and (3), where each contribution (e.g., vertical heave, solubility change, and AOU-related processes) is described in words. For this reason, we consider that adding an additional interpretation table within the main text would be somewhat redundant. However, to further enhance clarity without increasing the density of the main text, we have improved the interpretive descriptions within the main text and added a concise physical interpretation table associated with the schematic diagram in the Appendix. These improvement serves as a guide for readers who wish to connect the mathematical formulation with its physical interpretation. We believe that this approach preserves the streamlined structure of the main text while providing additional support for readers who benefit from a tabulated summary.

The following parts show the improved texts and additional Table A1 in the Appendix in the revised manuscript:

“The temporal changes in dissolved oxygen (O₂) were decomposed following the method of Sasano et al. [2015]. The processes underlying the oxygen tendency equations (Eqs. 2 and 3) are summarized below. We evaluated each contributing term and examined its relative importance for the dissolved O₂ trends. The total tendency of dissolved oxygen can be expressed as

$$\frac{\partial O_2}{\partial t} = \left(\frac{\partial O_2}{\partial z} \frac{\partial z}{\partial t} \right) + \left(\frac{\partial O_2^{sat}}{\partial t} \right)_{net} - \left(\frac{\partial (AOU)}{\partial t} \right)_{net} , \quad (2)$$

which can be rearranged as

$$\frac{\partial O_2}{\partial t} = \underbrace{\left(\frac{\partial O_2}{\partial z} \frac{\partial z}{\partial t} \right)}_{(i)} + \underbrace{\left(\frac{\partial O_2^{sat}}{\partial t} - \frac{\partial O_2^{sat}}{\partial z} \frac{\partial z}{\partial t} \right)}_{(ii)} + \underbrace{\left(-\frac{\partial(AOU)}{\partial t} + \frac{\partial(AOU)}{\partial z} \frac{\partial z}{\partial t} \right)}_{(iii)}. \quad (3)$$

(i) (ii) (iii) (iv) (v) (vi)

Here, $X = O_2, O_2^{sat}, AOU$ (Apparent Oxygen Utilization). The term $\partial z/\partial t$ denotes the temporal change in the depth of the isopycnal surface (z), while $\partial X/\partial z$ represents the vertical gradient of the variable X at that surface, averaged over the past 20 years. The net tendency term ($\partial X/\partial t$)_{net} represents the net changes associated with a variable X .

By applying Eq. (3), the rate of O_2 change (term i), which is the rate of reconstructed O_2 data estimated from the linear regression analysis, on each isopycnal surface can be decomposed into contributions from:

- (term ii) vertical heave acting on the vertical O_2 gradient;
- (term iii) solubility effects due to temperature and salinity changes;
- (term iv) vertical heave acting on the solubility gradient;
- (term v) AOU changes related to air-sea disequilibrium, biological activities, and lateral circulation
- (term vi) vertical heave acting on AOU gradients.

The derivation of Eqs. (2) and (3) follows Sasano et al. [2015] and is described in Appendix. A schematic illustration of this decomposition is provided in Supplementary Figure S5.

Figure 7 shows the horizontal distributions of the magnitude of each term on $25.0\sigma_\theta, 26.0\sigma_\theta,$ and $26.8\sigma_\theta$ surfaces. The results indicate that the prominent O_2 declines (Fig. 5c, f, i) arise from a combination of positive and negative contributions, with the dominant terms varying by latitude. In the high-latitude region around the Alaska Gyre in higher latitudes ($170^\circ\text{--}130^\circ\text{W}, 40^\circ\text{--}60^\circ\text{N}$), the largest negative contributions are associated with the deepening of isopycnal surfaces (term ii) and the vertical heave acting on the AOU gradient (term vi) (Fig. 7f, j, k, o). Because the dissolved oxygen generally decreases with depth ($\partial O_2/\partial z < 0$), deepening of isopycnal surfaces ($\partial z/\partial t > 0$) (Fig. 8 b–c) produces a negative contribution through vertical heave. Similarly, because AOU typically increases with depth, isopycnal deepening leads to an apparent increase in AOU, contributing negatively to dissolved O_2 via term (vi). In contrast, solubility-related changes (term iii) and net AOU tendencies (term v) act in opposite directions during this period (Fig. 7g–h, l–m). Taken together, these results are consistent with the strong negative O_2 trends observed in the Bering Sea on the $26.0\sigma_\theta$ and $26.8\sigma_\theta$ surfaces ($150^\circ\text{E}\text{--}170^\circ\text{W}, 50\text{--}60^\circ\text{N}$; Figs. 5f and i).”

Table A1 The physical interpretation of each term in the oxygen tendency decomposition shown in Eq. (3) and Eq. (C11) is summarized.

Term	Mathematical form	Physical interpretation
(ii)	$(\partial O_2 / \partial z)(\partial z / \partial t)$	Vertical heave acting on the O ₂ gradient
(iii)	$\partial O_2^{sat} / \partial t$	Solubility effect due to temperature and salinity changes
(iv)	$-(\partial O_2^{sat} / \partial z)(\partial z / \partial t)$	Vertical heave acting on the solubility gradient
(v)	$\partial AOU / \partial t$	AOU changes related to air–sea disequilibrium, biological activity and lateral circulation
(vi)	$-(\partial AOU / \partial z)(\partial z / \partial t)$	Vertical heave of the AOU gradient

6. The text is improved compared to the first submission but still contains numerous grammatical errors (e.g., inconsistent tense, missing articles, awkward constructions). For example:

>-“the magnitudes of the negative latitudes not necessary rely on the latitudes only” (p. 11)

The part can read now: “the magnitudes of negative O₂ trends do not depend monotonically on latitude alone” (Section 3.1)

>-“shifts horizontally rather than vertically” → ambiguous phrasing

The part can read now: “The 26.0σ_θ front exhibits primarily longitudinal, rather than meridional, shifts between 2004 and 2023” (Section 3.3.1)

>-“observed trends are connected smoothly each other” → needs rewriting

“how these trends occur and how they are connected” (Section 3.3.1)

> Maybe have professional English editing before acceptance.

Thank you for the suggestion. Owing to current funding limitations, we plan to use a professional English editing service at the minor revision stage, if required. For this revision, we carefully revised the manuscript using a paid language-editing tool to improve the English expression throughout all of the texts.

Responses to the comment from Reviewer #2

While the revised manuscript now includes many figures showing uncertainties, the authors describe only qualitative features. These uncertainties should be quantitatively compared with the magnitude of the trends, and then the signals that exceed the uncertainty should be discussed. Since oxygen concentration in GOBAI-O₂ is estimated by using temperature and salinity information, detected signals should be fully evaluated by taking their uncertainties into account before discussing physical implications.

Thank you for this comment. The GOBAI-O₂ dataset was generated using machine-learning algorithms trained to estimate dissolved O₂ from absolute salinity, conservative temperature, potential density anomaly, hydrostatic pressure, bottom depth, and additional spatiotemporal information, as described in Sharp et al. (2023). As we are not the developers of the GOBAI-O₂ product, it is difficult for us to independently reassess its uncertainty structure beyond what has already been documented. The characteristics and sources of uncertainty in GOBAI-O₂ have been thoroughly discussed by the data developers (Sharp et al., 2023). In this study, we therefore make use of the uncertainty estimates provided with the GOBAI-O₂ dataset. We now present these uncertainty fields alongside the spatial distributions of the linear trends in Figs. 1 and 3, allowing readers to visually assess the relative magnitudes of the trends and uncertainties. In addition, we have evaluated the statistical significance of the estimated linear trends using a Student's t-test with effective degrees of freedom that account for lag-1 autocorrelation (Figs. 1a–u and 3). The results show that many of the detected oxygen trends, particularly those below the surface (Fig. 1o), are statistically significant at the 95% confidence level. This additional analysis allows readers to distinguish robust signals from regions where trends are not statistically significant, thereby providing a more quantitative basis for the subsequent physical interpretation.

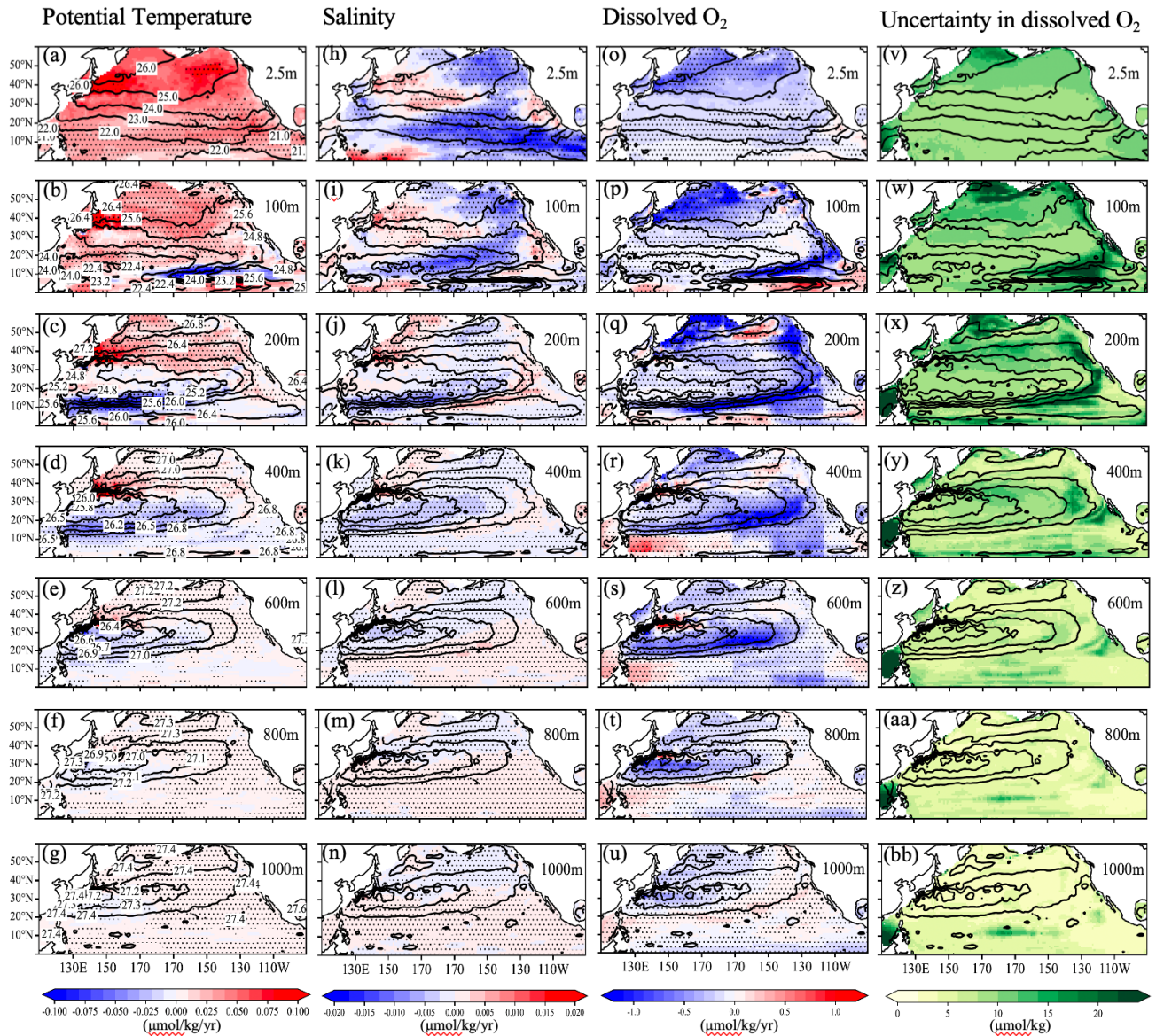
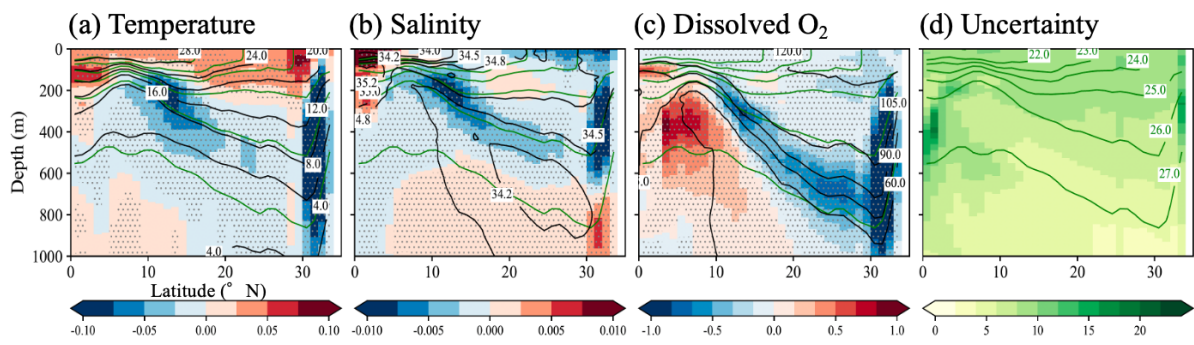


Figure 1 in revised manuscript: Horizontal distributions of linear trends ($\mu\text{mol/kg/yr}$) in (a–g) potential temperature, (h–n) salinity, and (o–u) dissolved oxygen (O₂) during the observational period at depths of 0, 100, 200, 400, 600, 800, and 1000 m, respectively. Hatched areas indicate statistically significant trends at the 95% confidence level based on a t-test with effective degrees of freedom accounting for temporal autocorrelation. Trend significance was evaluated using a Student’s t-test with effective degrees of freedom accounting for lag-1 autocorrelation. Contours denote potential density at each depth. Labels for the potential density are shown only in the potential temperature sections. Corresponding distributions of the mean uncertainty in dissolved O₂ ($\mu\text{mol/kg}$) are presented in panels (v–bb).

137° E line



165° E line

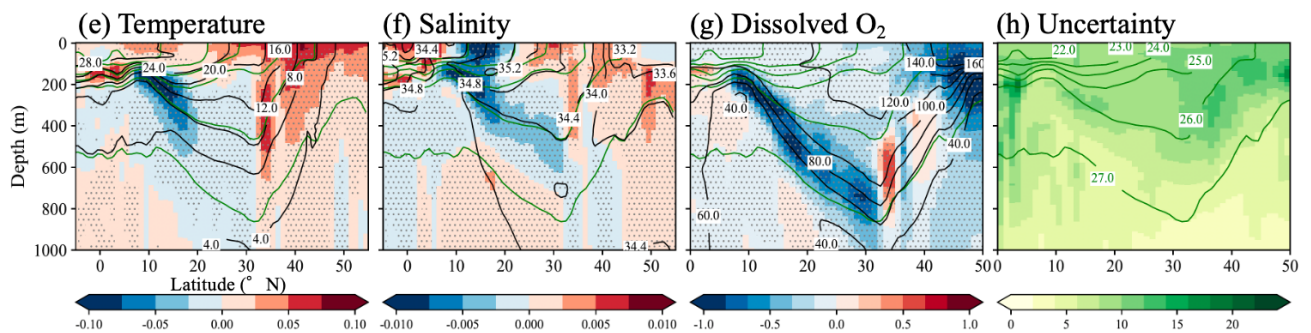


Figure 3 in the revised manuscript: Vertical sections showing linear trends in potential temperature (a, e), salinity (b, f), and dissolved O₂ (c, g) along the 137°E and 165°E meridians, respectively. Corresponding vertical sections of the mean uncertainty are presented in panels (d) and (h). Black contour lines indicate the mean potential temperature (a, e), salinity (b, f), and dissolved oxygen (c, g) over the period 2004–2023, while green contour lines represent the mean potential density. Labels for the potential density are shown only in the uncertainty sections. Hatched areas indicate statistically significant trends at the 95% confidence level based on a Student’s t-test with effective degrees of freedom accounting for temporal autocorrelation. Trend significance was evaluated using a t-test with effective degrees of freedom accounting for lag-1 autocorrelation.